2 of 3

SSD-TDR-64-96

The Combined Aerodynamic-Propulsive Orbital Plane-Change Maneuver

56 p
hc ~ 3.00
mf ~ 0.50

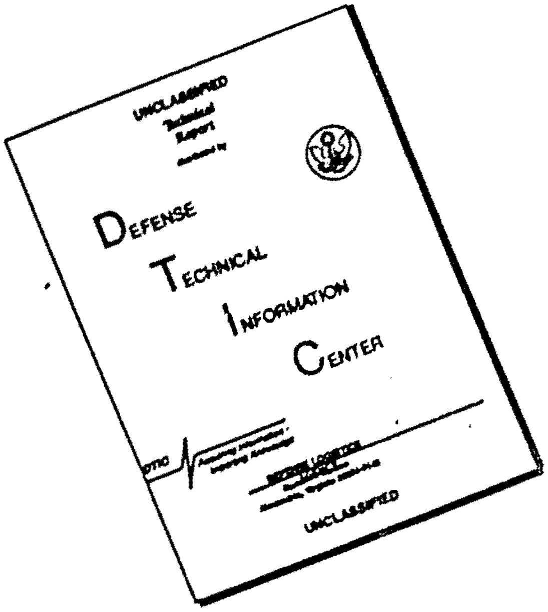
10 JUNE 1964

Prepared by R. W. BRUCE
Astrodynamics Department
Guidance and Control Subdivision
Electronics Division

Prepared for COMMANDER SPACE SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

EL SEGUNDO TECHNICAL OPERATIONS • AEROSPACE CORPORATION
CONTRACT NO. AF 04(695)-269

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

SSD-TDR-64-98

Report No.
TDR-269(4550-10)-9

THE COMBINED AERODYNAMIC-PROPULSIVE ORBITAL PLANE-CHANGE MANEUVER

Prepared by

R. W. Bruce
Astrodynamics Department
Guidance and Control Subdivision
Electronics Division

El Segundo Technical Operations
AEROSPACE CORPORATION
El Segundo, California

Contract No. AF 04(695)-269

10 June 1964

Prepared for

COMMANDER SPACE SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

SSD-TDR-64-98

Report No.
TDR-269(4550-10)-9

THE COMBINED AERODYNAMIC-PROPULSIVE ORBITAL PLANE-CHANGE MANEUVER

Prepared by:

Richard W. Bruce
Astrodynamics Department

Approved by:

C. M. Price, Head
Astrodynamics Department

E. Levin, Director
Guidance and Control Subdivision

This technical documentary report has been reviewed and is approved for publication and dissemination. The conclusions and findings contained herein do not necessarily represent an official Air Force position.

For Space Systems Division
Air Force Systems Command

Edward D. Harney
Lt Col, USAF
Studies and Analysis Division

El Segundo Technical Operations
AEROSPACE CORPORATION
El Segundo, California

ABSTRACT

Due to the relative expense of the orbital plane-change maneuver when it is accomplished by means of impulsive thrust, other techniques have been sought that would be more economical from the standpoint of required characteristic velocity. Two techniques that make use of combined aerodynamic and propulsive forces have been proposed by London and Nyland. These are reviewed, and their limitations, which are due in part to certain simplifying assumptions made in their analyses, are presented. This investigation demonstrates that both analyses, while valuable because they are presented in closed form, are limited to plane changes below 30 to 40 degrees. It is also shown that the combined maneuver is superior to the impulsive-thrust plane change for vehicles with lift-to-drag ratios greater than 1.5 and that the velocity savings that result as a consequence of using such maneuvers are on the order of 4000 to 5000 ft/sec, at most. As a result, it is concluded that, for certain situations, the combined aerodynamic-propulsive maneuver appears to be an attractive and available means for reducing the characteristic velocity requirement of the orbital plane change.

CONTENTS

FIGURES

FIGURES (Continued)

FIGURES (Continued)

I. INTRODUCTION

Of all the various types of purely propulsive satellite maneuvers used to change the size, shape, and orientation of the orbit in space, the most expensive in terms of characteristic velocity required is the orbital plane change maneuver. For moderate to large plane changes, the characteristic velocity requirement, ΔV, can be reckoned in terms of thousands of feet per second for near-earth satellite orbits, as compared with the maneuvers that change the orbit size and shape and require from one to two orders of magnitude less velocity. This fact is illustrated in Fig. 1, where the characteristic velocity required to change the plane of a satellite in a circular orbit at 300 n mi altitude is compared with that required to change apogee (or perigee). The relative expense of the purely propulsive plane-change maneuver has led to a search for other techniques that could be used to effect orbital plane changes that would be more economical from the standpoint of required characteristic velocity. One of the most interesting of these new techniques makes use of combined aerodynamic and propulsive forces. This technique has been treated in the literature by London (Ref. 1), and Nyland (Ref. 2), and the predicted saving in required characteristic velocity is striking. For example, following Nyland's analysis, it is pointed out that an aerodynamic satellite vehicle with a lift-to-drag (L/D) ratio of 2 can accomplish a 60 deg orbital plane change at 300 n mi with a possible saving in ΔV (when compared with the basic single-impulse propulsive plane-change maneuver) of about 7800 ft/sec. Substantial savings in ΔV are also predicted for smaller plane-change angles and for vehicles with smaller L/D ratios. Even greater velocity savings are predicted by the technique of London. Both of the above mentioned analyses have been presented in closed form. For that reason they are valuable tools for examining the interplay between the significant parameters to a greater extent than would be practicable from a high-speed computer study. However, some of the assumptions made by London and Nyland, which enable solutions in closed form, also have the effect of limiting the regions of

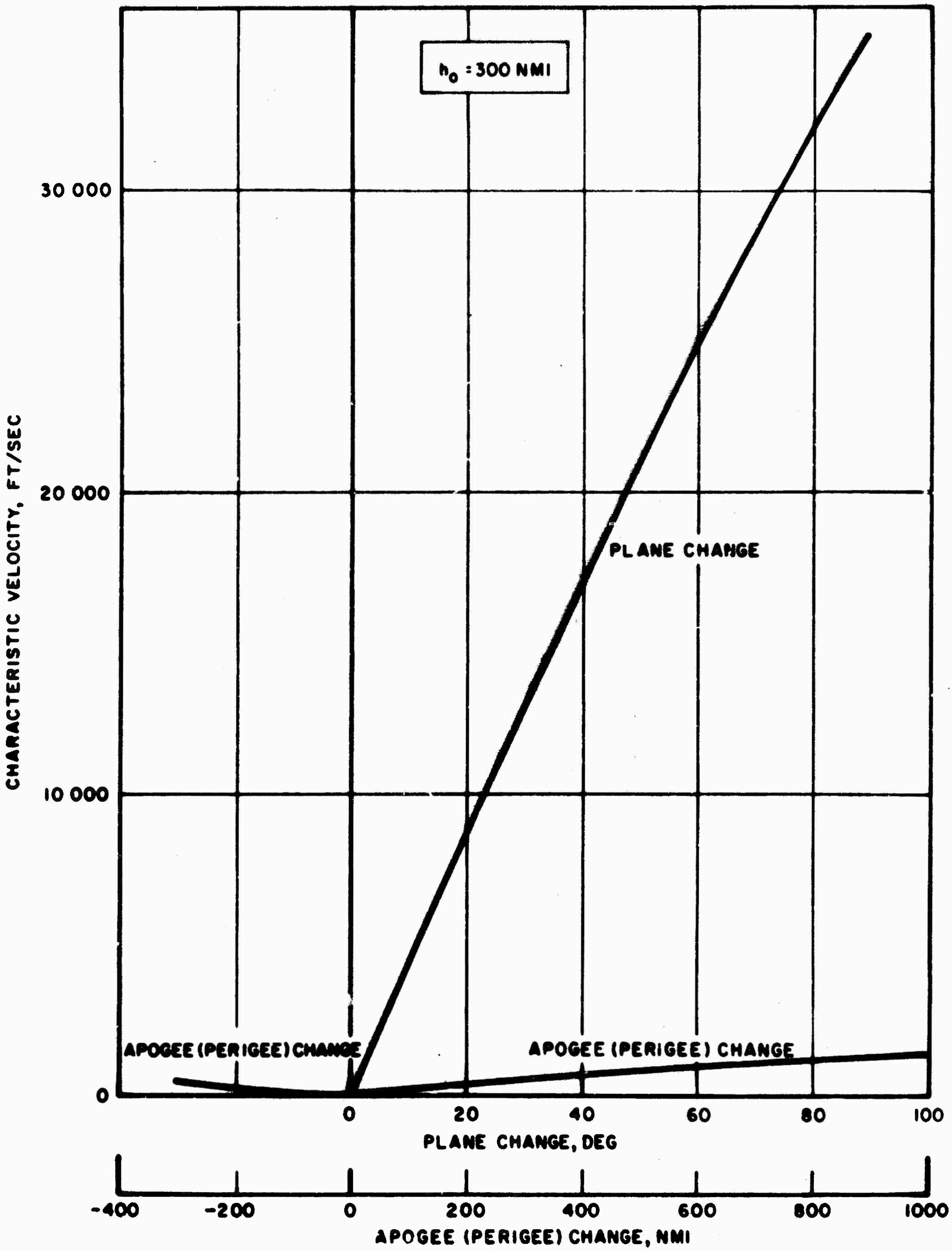


Figure 1. Characteristic Velocity Required for Plane Change vs Apogee (Perigee) Change

applicability of their analyses. To a certain extent, London (Ref. 3) discusses some of the limitations of his method.

It is the purpose of this study, based on computer results, to describe in greater detail the regions where the assumptions made by London and Nyland are applicable.

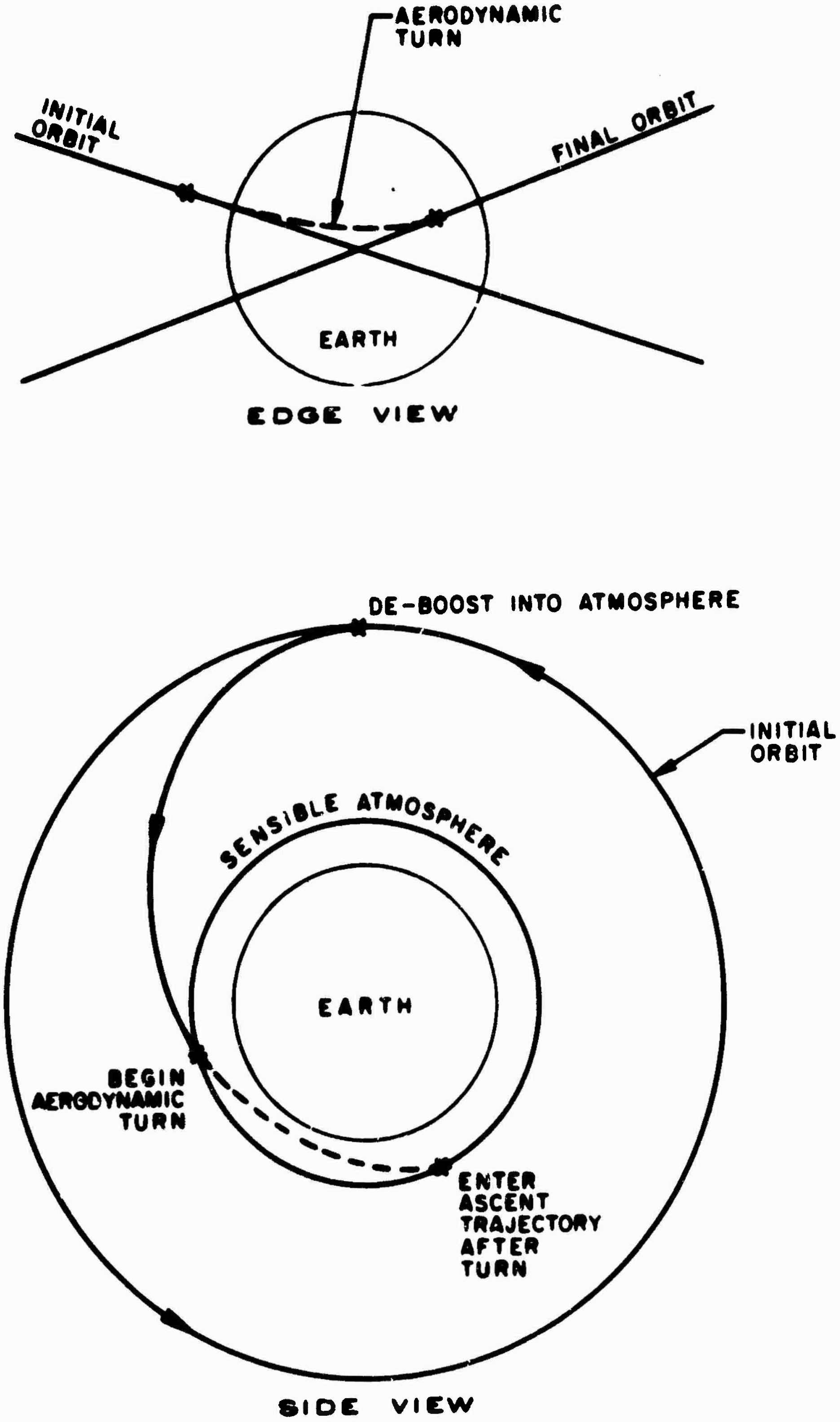


Figure 2. Geometry of the Combined Aerodynamic-Propulsive Plane Change Maneuver

II. THE COMBINED AERODYNAMIC-PROPULSIVE MANEUVER

The combined plane-change maneuver can be described generally as one in which the satellite vehicle, with lifting surfaces, is first propulsively deflected from its orbit into the atmosphere, at which point an aerodynamic turn is initiated. Upon completion of the turn the energy lost by the vehicle due to drag is then restored by means of rocket thrust, such that the original orbit is re-established in a new plane. The maneuver is graphically illustrated in Fig. 2.

A. THE ANALYSIS OF LONDON

In the approach taken by London the maneuvering vehicle flies the aerodynamic portion of its trajectory with constant angle of attack and constant bank angle. The aerodynamic properties of the vehicle are assumed to be constant for any specified attitude. The angle of attack is chosen such as to result in a condition of maximum L/D ratio. The bank angle is chosen together with the re-entry angle such as to result in a particular value of velocity heading change at the completion of the aerodynamic portion of the trajectory. For example, if it is desired to change the plane of a circular orbit at 300 statute miles (statute units are employed throughout London's analysis) the satellite is deflected into the atmosphere with a component of impulsive velocity such that re-entry at a specified re-entry angle, say -6 deg, will occur at 50 stat mi. This component of ΔV is determined both in direction and magnitude from the analysis of Low (Ref. 4). At the point of re-entry the angle of attack of the vehicle which corresponds to maximum L/D is established, and the vehicle is banked by an amount predicted by London's analysis such that the desired velocity heading change of 30 deg will result. The aerodynamic portion of the trajectory is considered terminated when the vehicle re-attains an altitude of 50 stat mi. At this point the vehicle is given a second velocity impulse to effect a transfer to the original 300 stat mi altitude, where a final velocity impulse is applied to circularize the orbit.

A basic question regarding London's analysis arises, however, as to whether the satellite vehicle does indeed re-attain the 50 stat mi altitude (by definition) at the completion of the aerodynamic turn in every instance. Whether or not the vehicle skips out of the atmosphere depends upon the magnitude of the lift forces in the radial direction, relative to all other forces. And, as the vehicle is banked to increase its turning capability, the radial lift forces tend to be reduced. In light of the above question, a computer study was performed in order to determine whether skip-out would occur for the following range of the pertinent parameters.

1. Initial altitude, h_o = 300 stat mi
2. Re-entry altitude, h_E = 50 stat mi
3. Re-entry angle, $\gamma_E = -2 \rightarrow -10$ deg
4. Lift-to-drag ratio, $L/D = 1 \rightarrow 4$
5. Lift coefficient, C_L(@ L/D max) = $\rightarrow 0.25$
6. Wing loading, $W/S = 25 \rightarrow 50$ lb/ft^2
7. Re-entry velocity, V_E; uniquely determined by specifying h_o, h_E, and γ_E
8. Velocity heading change, $\Delta\eta = 0 \rightarrow 90$ deg (easily convertible to plane change)
9. Bank angle, β; uniquely determined following London's analysis by specifying γ_E and $\Delta\eta$.

In the series of aerodynamic maneuvers studied, the computed trajectories were generally typical of one or another of those shown in Fig. 3 depending upon such factors as the magnitude of the bank angle, β. In order to present a meaningful comparison between the computed results and the analytical predictions of London, it was decided to plot the change in velocity heading that had accrued at the point of exit from the atmosphere versus the parameter, $C_L S/W$, for various bank angles and L/D ratios. In cases where no skip occurred the change in velocity heading at the peak altitude reached by the vehicle was used. Trajectories in which the altitude monotonically decreased with time were discarded. Shown in Figs. 4 through 7 are the results for a re-entry angle of -6 deg. The computed value of $\Delta\eta$ is shown

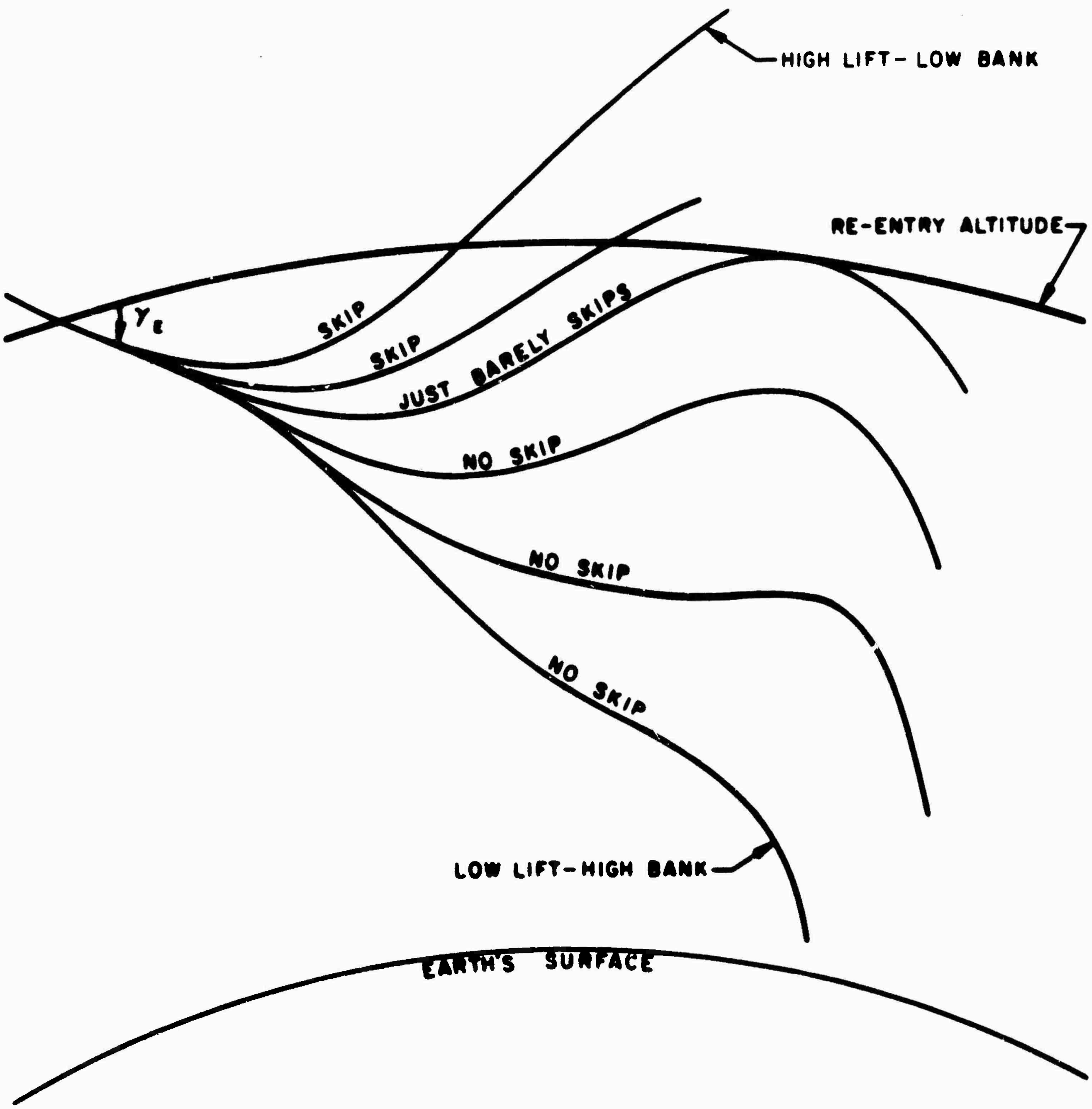


Figure 3. Typical Re-entry Trajectories

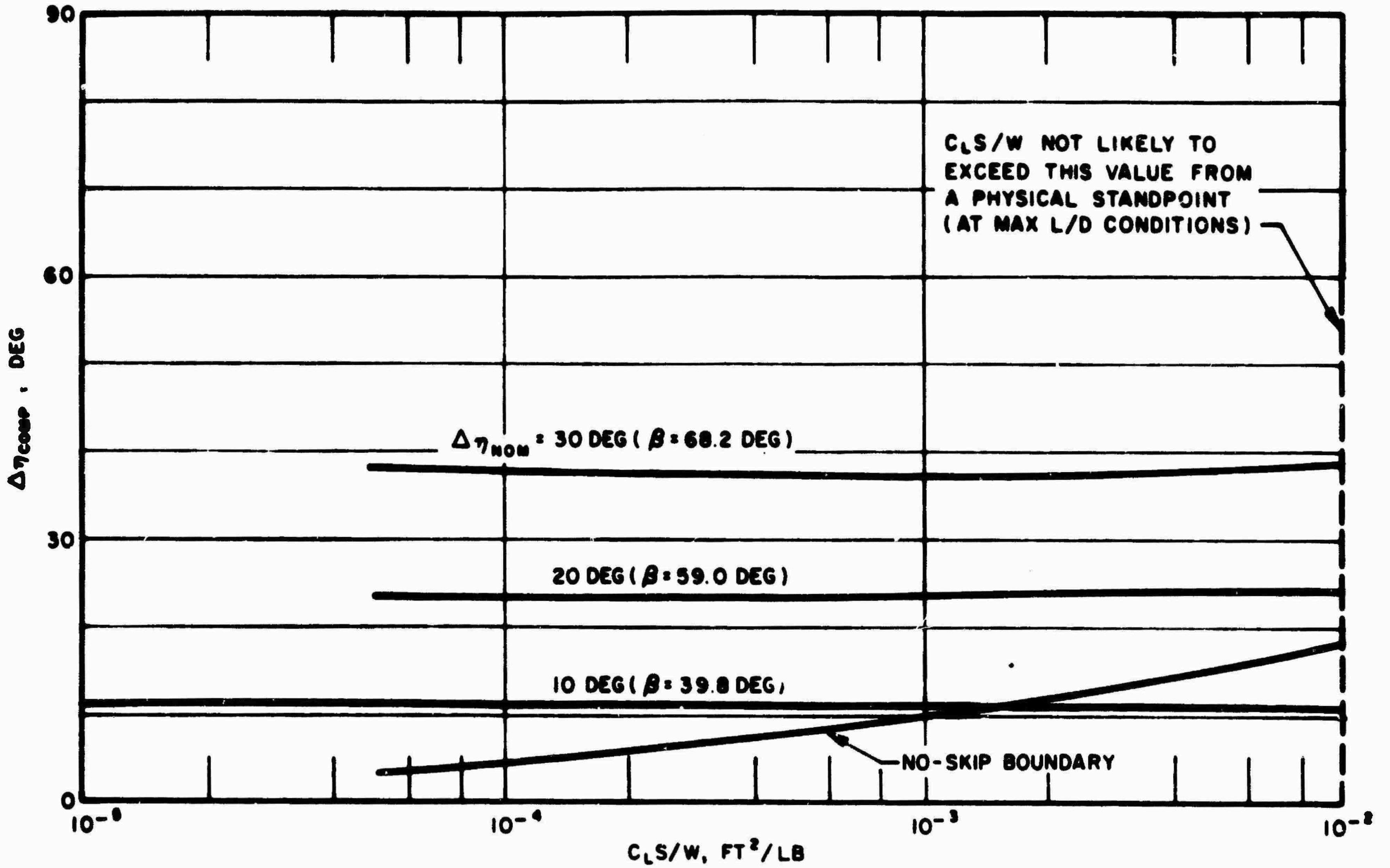


Figure 4. Computed Velocity Heading Change as a Function of C_LS/W for Various Bank Angles: γ_E = -6 deg, L/D = 1

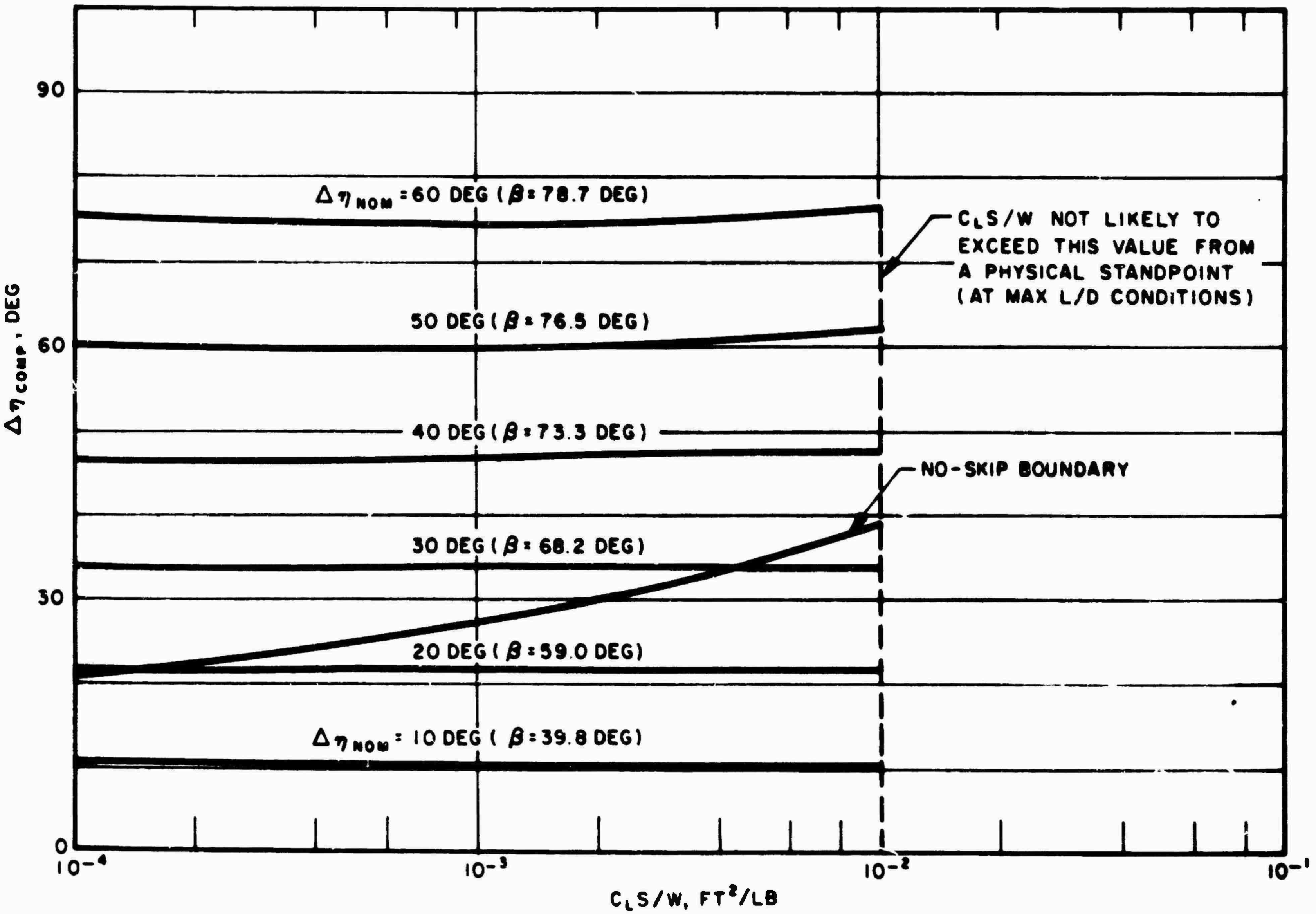


Figure 5. Computed Velocity Heading Change as a Function of $C_L S/W$ for Various Bank Angles: γ_E = -6 deg, L/D = 2

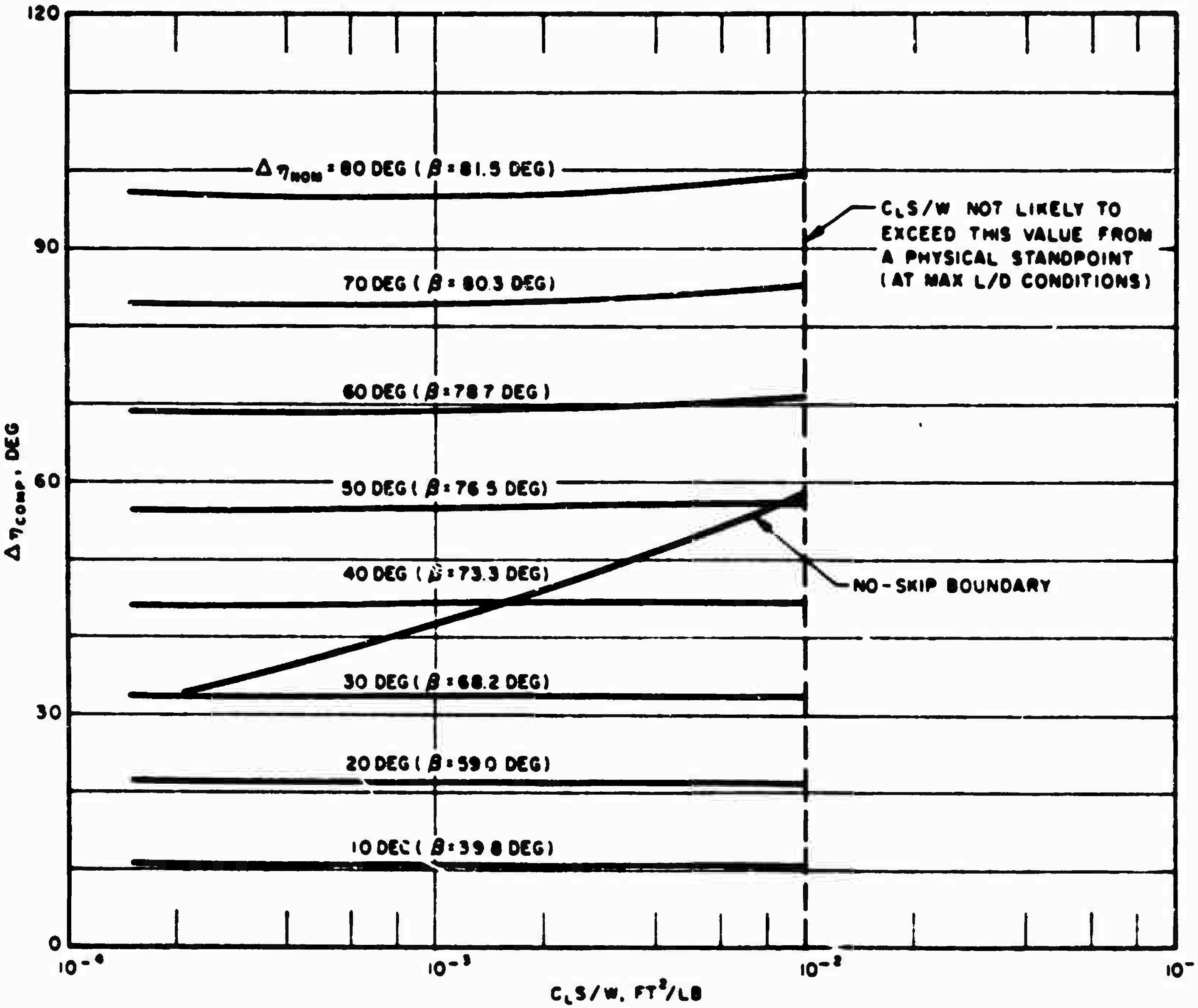


Figure 6. Computed Velocity Heading Change as a Function of $C_L S/W$ for Various Bank Angles: $\gamma_E = -6$ deg, L/D = 3

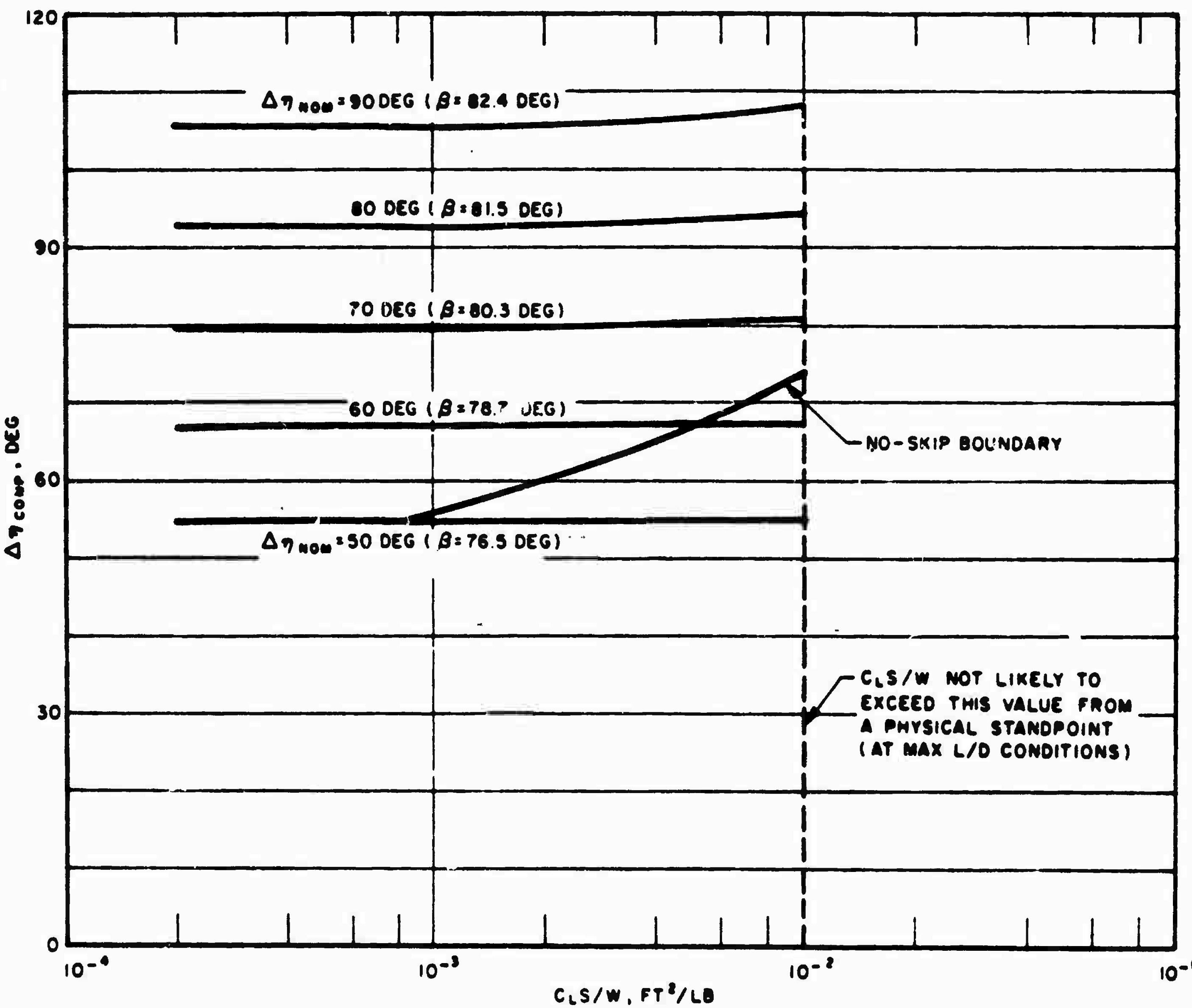


Figure 7. Computed Velocity Heading Change as a Function of C_LS/W for Various Bank Angles: γ_E = -6 deg, L/D = 4

on the ordinate as a function of $C_L S/W$. The family of curves corresponds to those values of the bank angle, β, that would result in the velocity heading changes predicted by London's analysis, as indicated. As an example, in Fig. 4, for a value of $C_L S/W$ equal to 10^{-2} ft^2/lb, (which is about as large as can be realized from a physical standpoint at present) it is seen that the predicted value of $\Delta\eta$ equal to 10 deg is in excellent agreement with the computed value of $\Delta\eta$ equal to 11 deg. However, subject to the criterion that the vehicles skip out of the sensible atmosphere, it is seen that a $\Delta\eta$ of about 18 deg (the point on the no-skip boundary) is the most that can be attained for the conditions specified. Furthermore, as will be discussed later, the above heading change of 18 deg can be accomplished more economically by a single impulsive ΔV application at 300 stat mi. As L/D increases, the $\Delta\eta$ attainable also increases, and it also will be shown that aerodynamic plane changes become more economical than the impulsive plane changes for the high L/D cases. In such cases the analysis of London, where applicable, predicts $\Delta\eta$ fairly well (it underestimates the maximum attainable $\Delta\eta$ by about 15 percent for the L/D values considered).

The no-skip boundaries appearing in Figs. 4 through 7 have been summarized in Fig. 8. It is felt that the aerodynamic maneuvering technique of London, together with his closed-form analysis, is applicable in the region below the no-skip boundaries, subject to a 15 percent error in the estimation of $\Delta\eta$.

Similar results were computed for re-entry angles of -2 and -10 degrees, as well. These are shown in Figs. 9 through 16. Note in Fig. 12, where the no-skip boundaries for a re-entry angle of -2 degrees are summarized, that changes in velocity heading of 10 to 20 degrees are the most that can be attained. On the other hand, for the -10 degree re-entry angle case, velocity heading changes up to 90 degrees can be attained, as seen in Fig. 16. However, other factors such as aerodynamic g-loading and heating can be excessive (e.g., g's > 30) for re-entry angles on the order of -10 deg, and for this reason such cases are not considered practical.

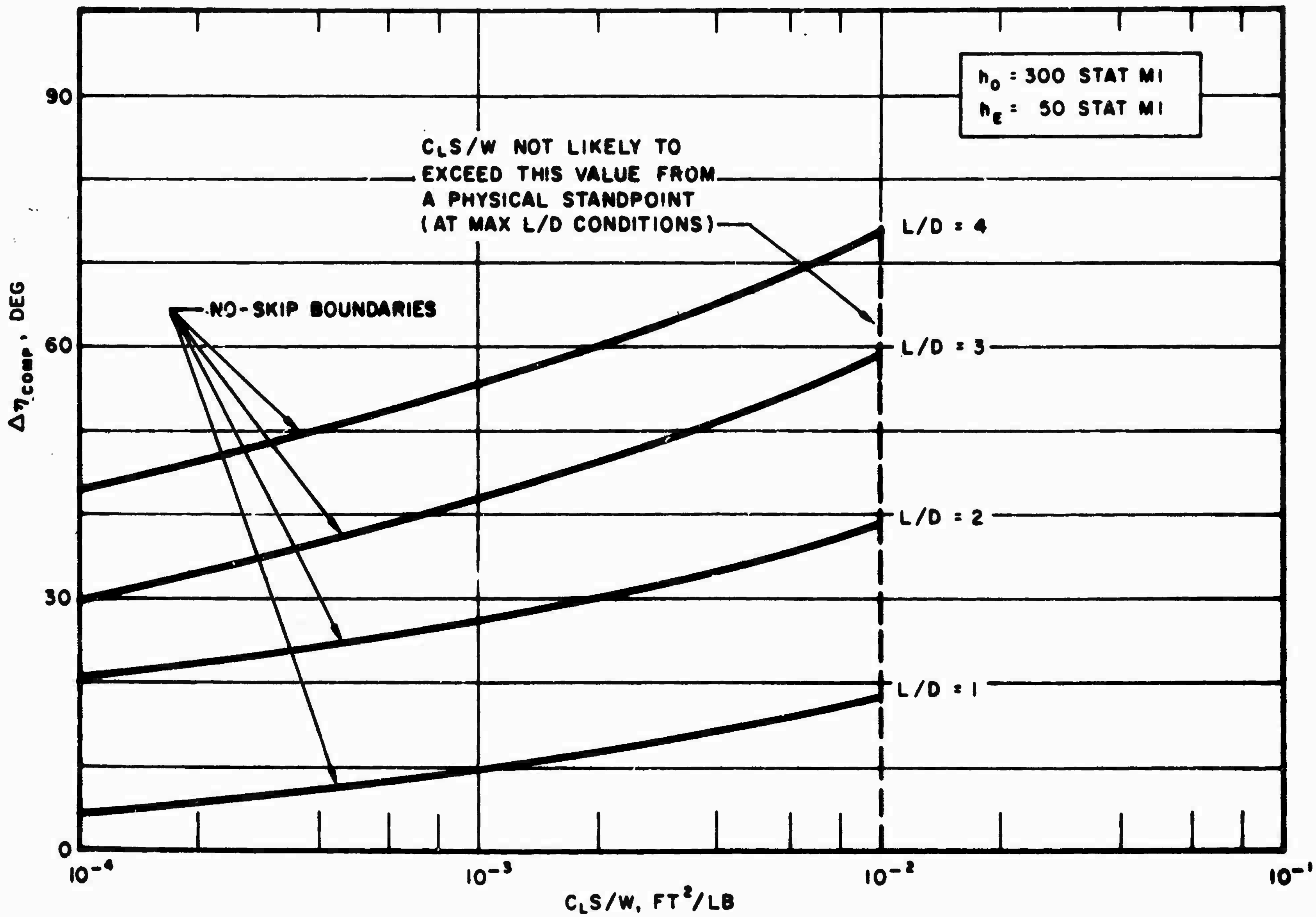


Figure 8. Summary of No-Skip Boundaries, γ_E = -6 deg

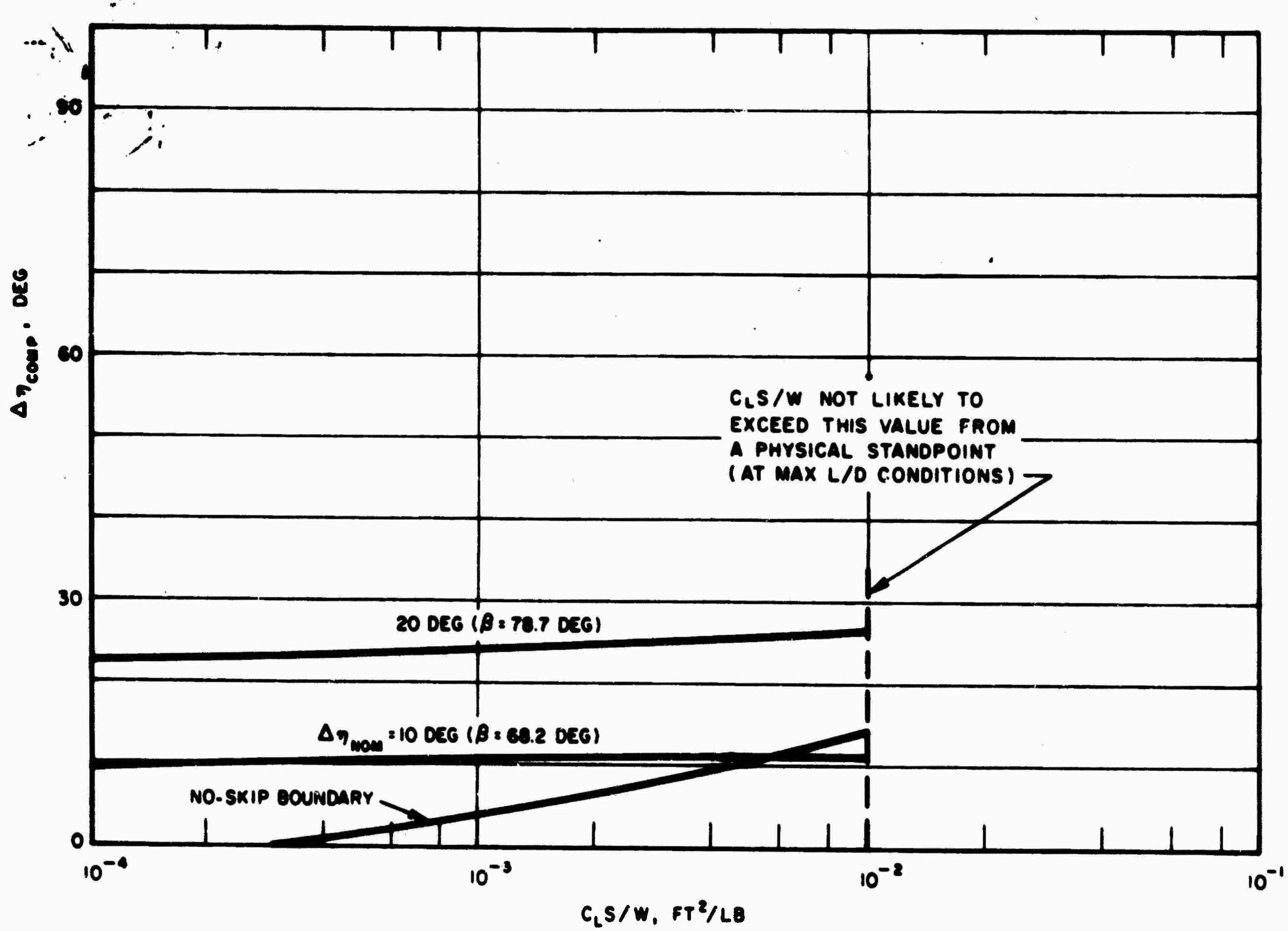


Figure 9. Cor. puted Velocity Heading Change as a Function of C_LS/W for Various Bank Angles: γ_E = -2 deg, L/D = 2

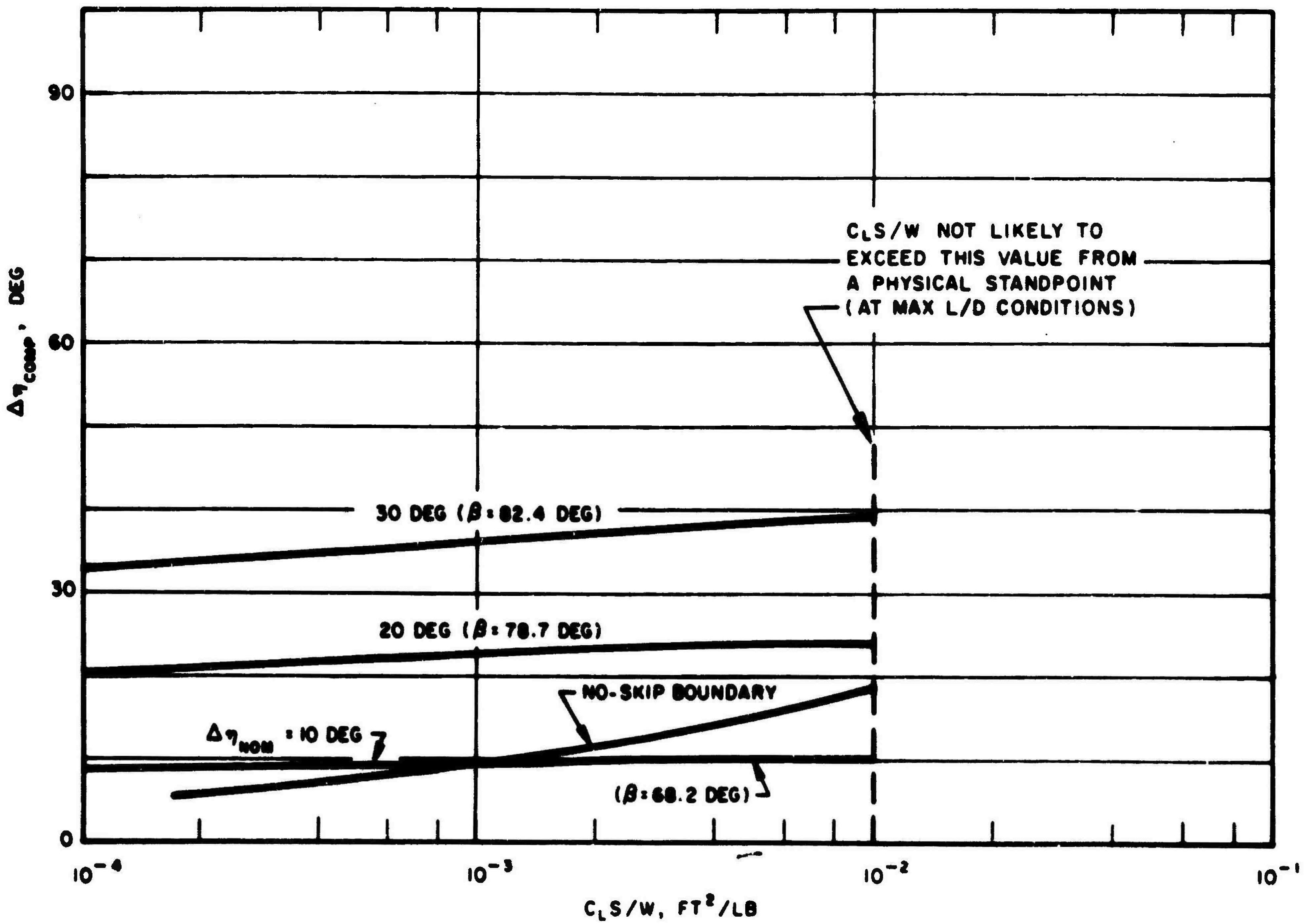


Figure 10. Computed Velocity Heading Change as a Function of $C_L S/W$ for Various Bank Angles: γ_E = -2 deg, L/D

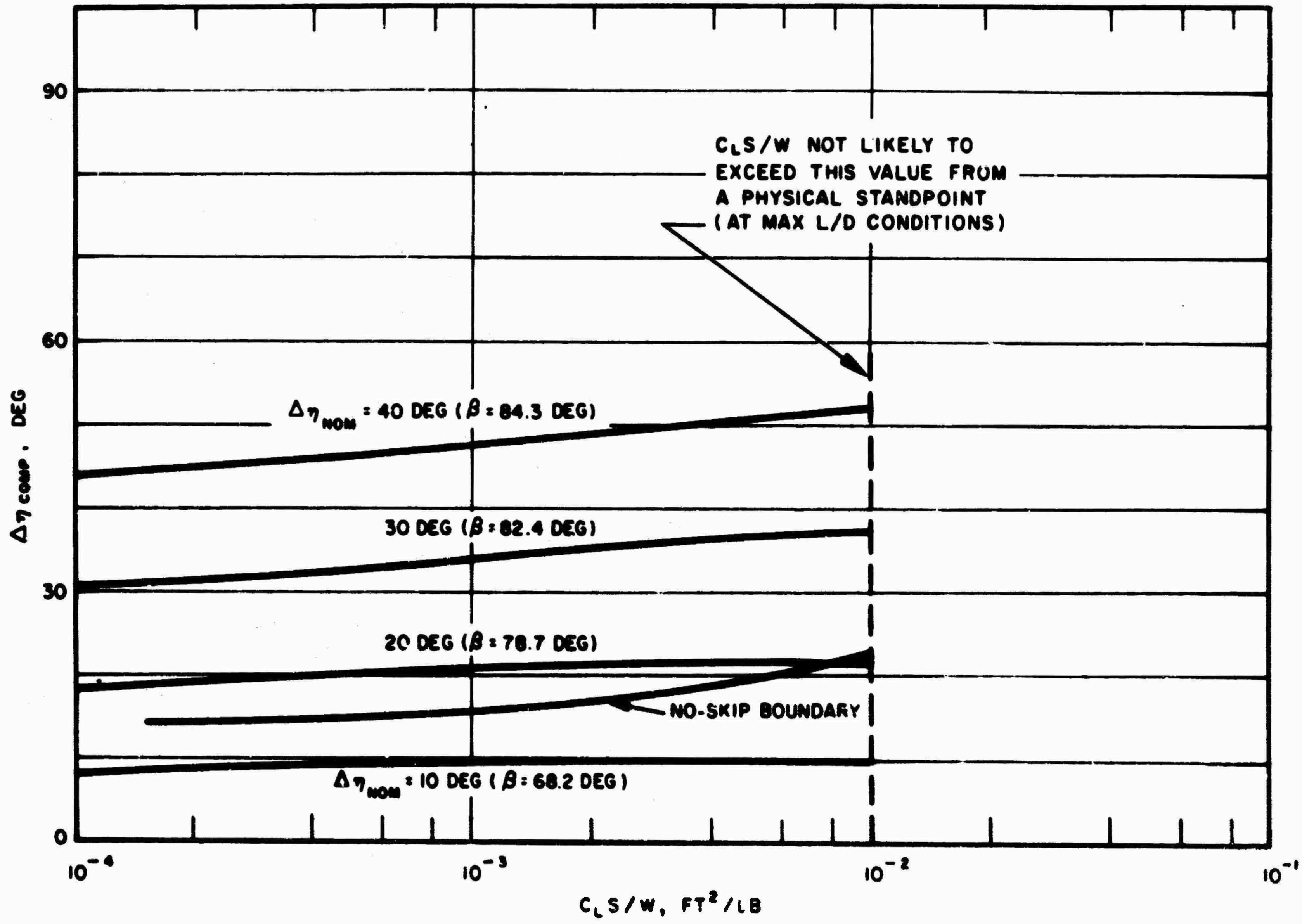


Figure 11. Computed Velocity Heading Change as a Function of C_LS/W for Various Bank Angles: γ_E = -2 deg, L/D = 4

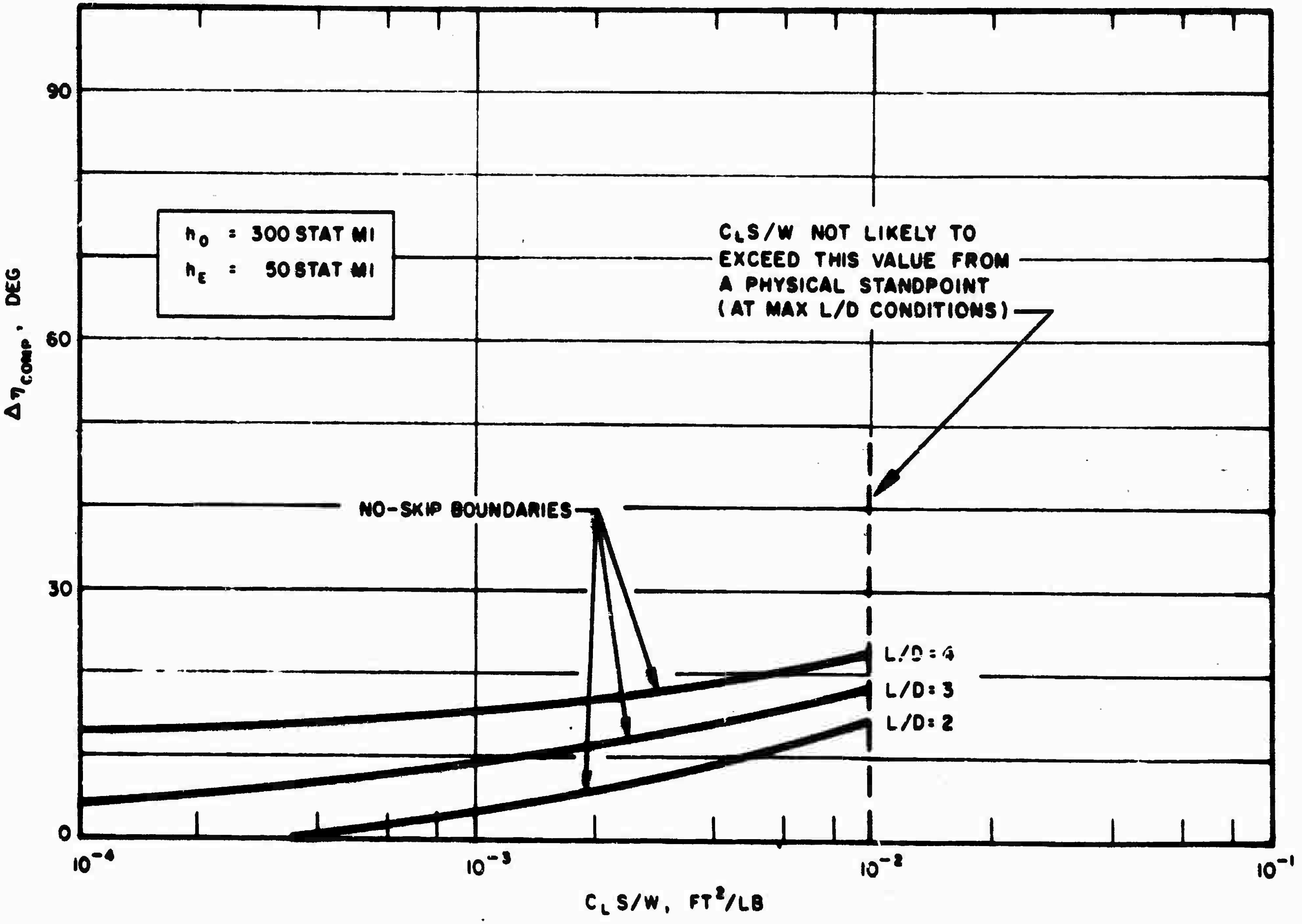


Figure 12. Summary of No-Skip Boundaries, γ_E = -2 deg

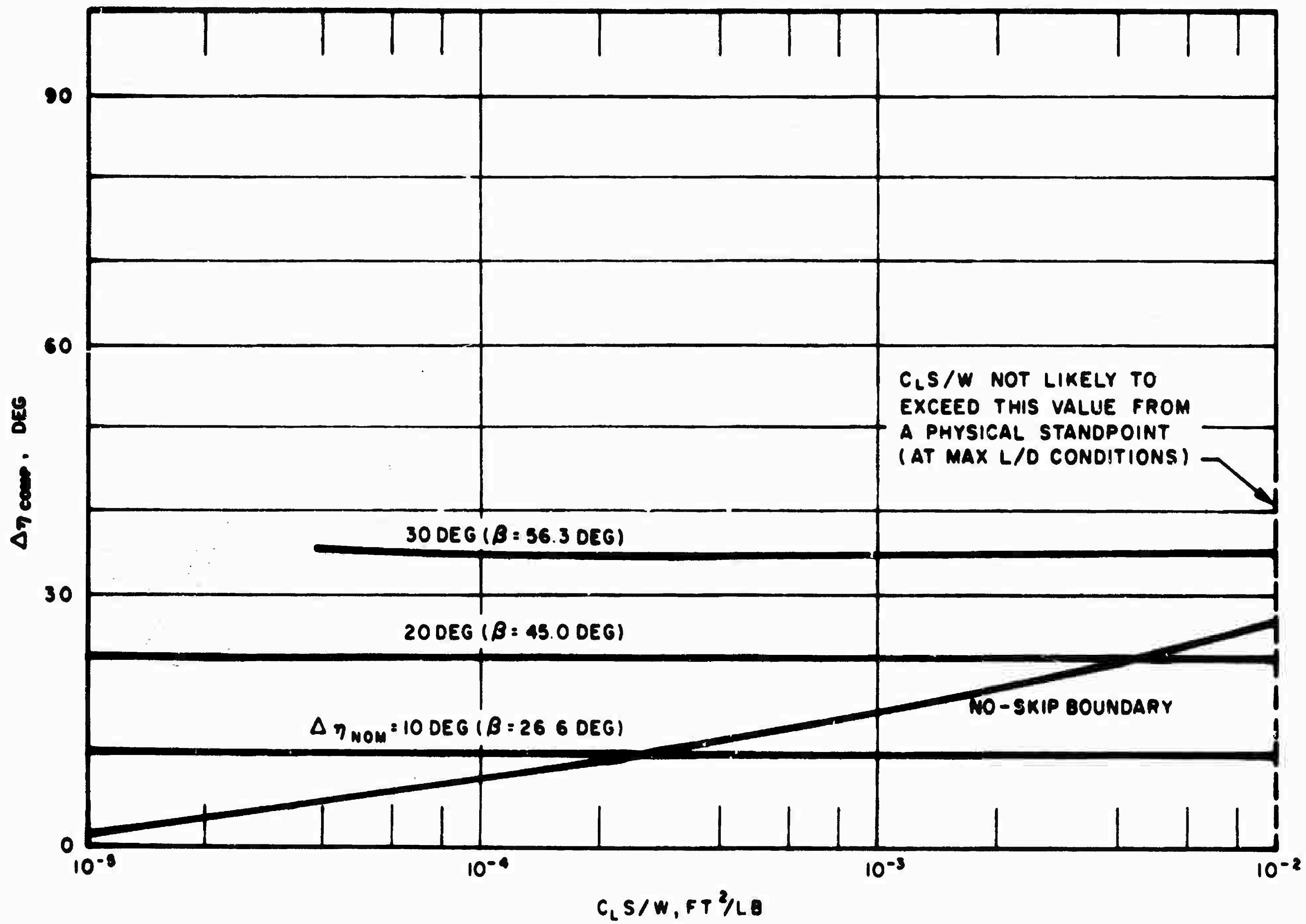


Figure 13. Computed Velocity Heading Change as a Function of $C_L S/W$ for Various Bank Angles: γ_E = -10 deg, L/D = 1

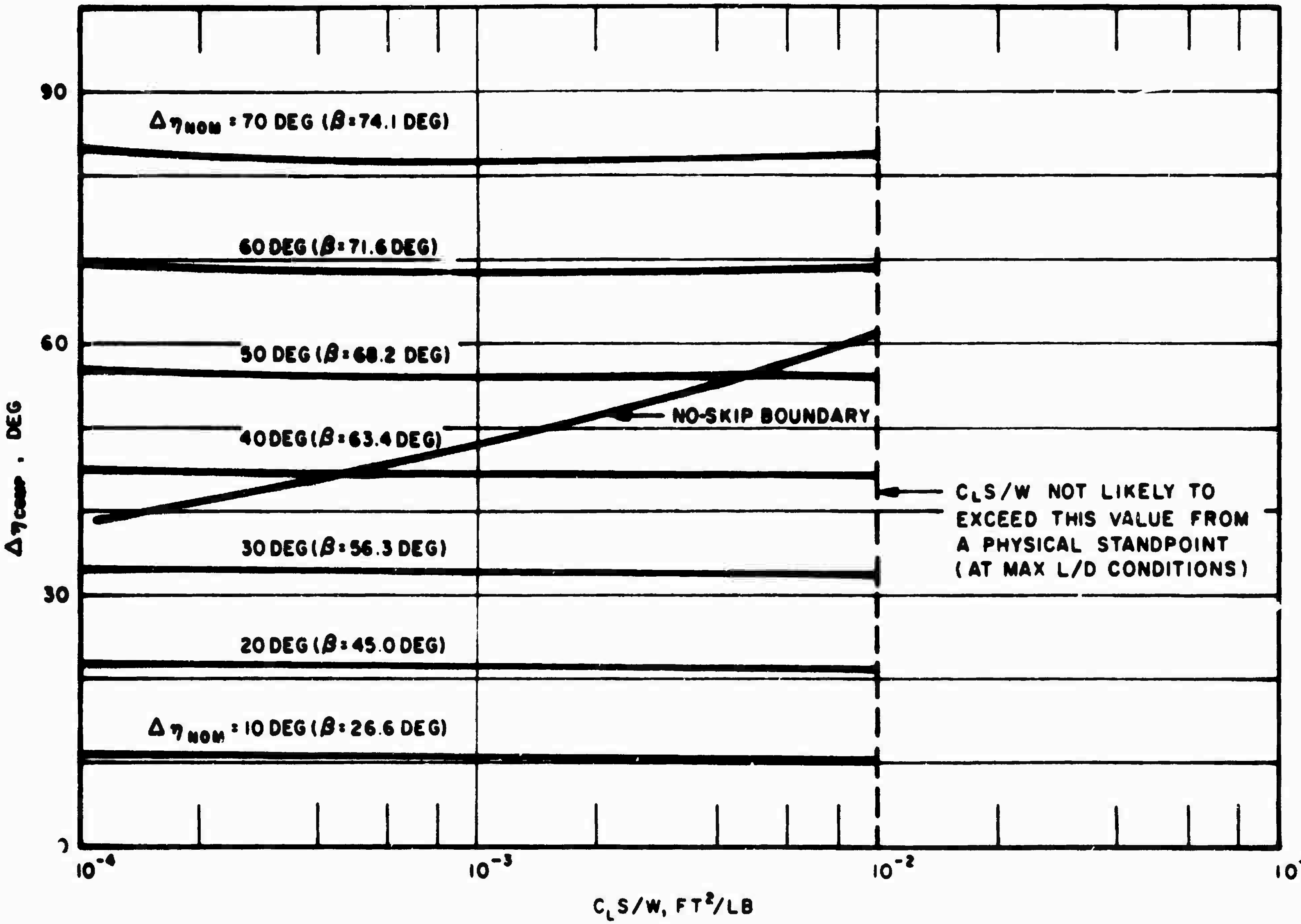


Figure 14. Computed Velocity Heading Change as a Function of C_LS/W for Various Bank Angles: γ_E = -10 deg, L/D = 2

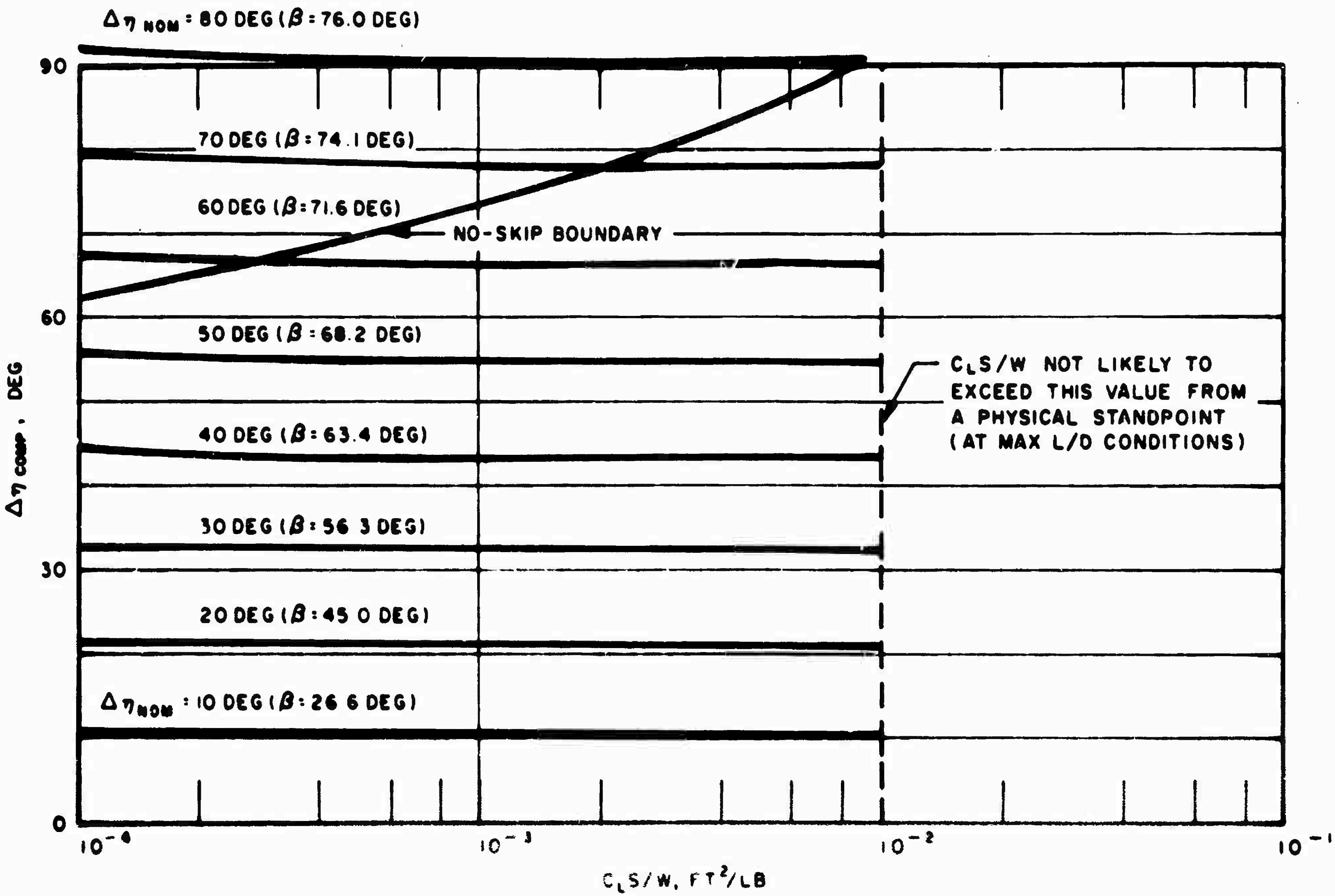


Figure 15 Computed Velocity Heading Change as a Function of $C_L S/W$ for Various Bank Angles: γ_E = -10 deg, L/D = 3

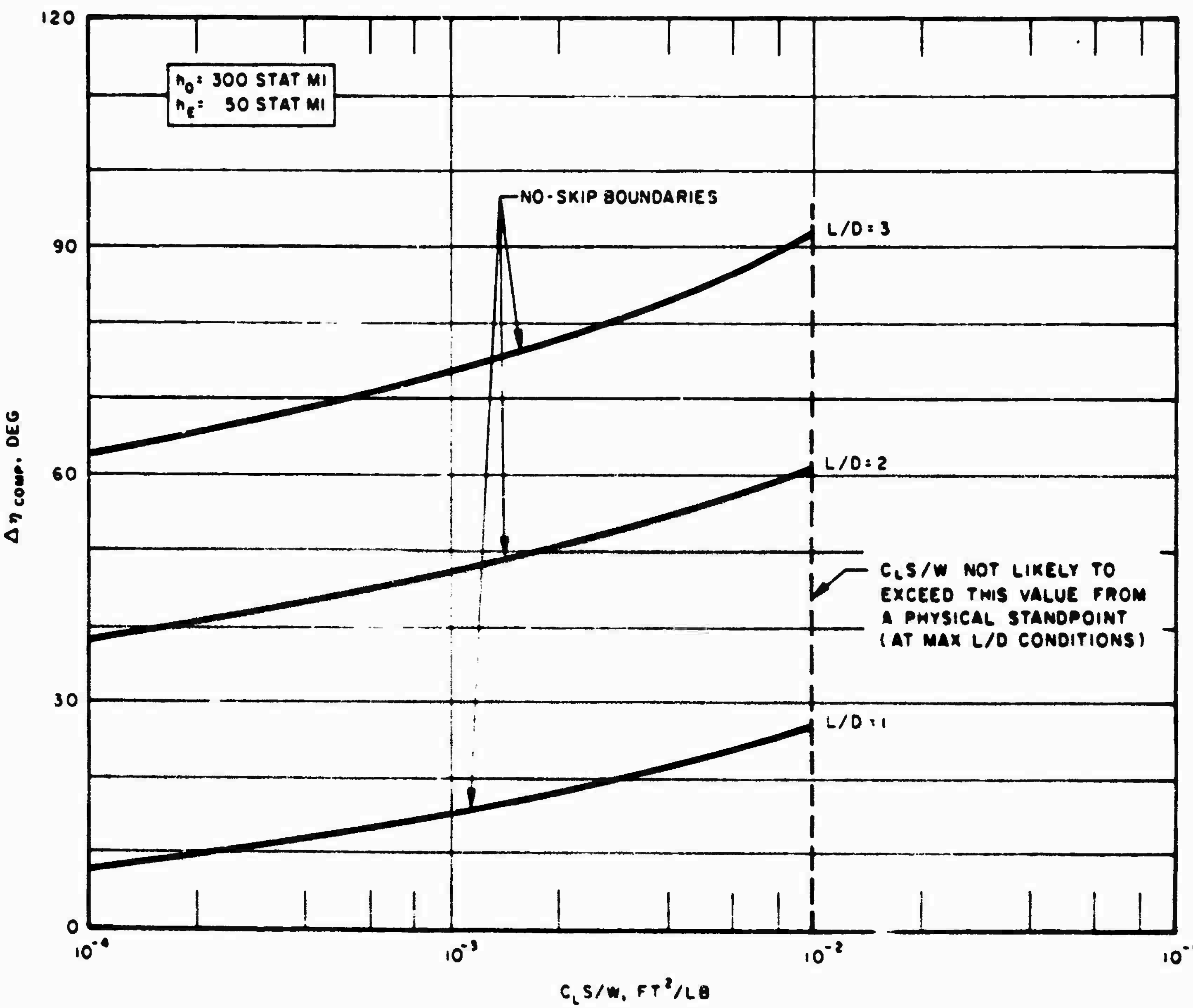


Figure 16. Summary of No-Skip Boundaries, γ_E = -10 deg

The total required characteristic velocity for the maneuvers previously discussed was also computed and is shown in Figs. 17 through 19 for a re-entry angle of -6 deg and three values of $C_L S/W$—namely, 0.001, 0.005, and 0.01 ft^2/lb. Also included in the figures for purposes of comparison are those values of ΔV as predicted by London's analysis. Note that the agreement, where applicable, is quite good, being in error at most by 100 to 300 ft/sec. The most important comparison, however, is between the ΔV required for the combined aerodynamic-propulsive plane change, following London's method, and that required by the purely propulsive plane change. Shown also in Figs. 17 through 19 is the curve of ΔV vs $\Delta \eta$ for the impulsive thrust case. It now becomes evident where the combined maneuver is advantageous from the standpoint of required characteristic velocity. For example, it is seen in Fig. 18 that a saving in ΔV of about 3600 ft/sec can be expected for a 30 deg change in velocity heading ($L/D = 2$, $\gamma_E = -6$ deg, $C_L S/W = 0.005$ ft^2/lb) over the impulsive thrust case. A convenient summary of the regions where the combined aerodynamic-propulsive maneuver is superior is shown in Fig. 20. A similar summary for re-entry angles of -2 and -10 deg has not been included because it was felt that in the former case the resulting values of $\Delta \eta$ were not large enough to warrant serious consideration, and, that in the latter case other factors such as g-loading and heating were prohibitive.

The combined maneuver is also superior at altitudes higher than the 300 stat mi example considered in this study; however, there is a point beyond which its superiority is lost. This is partly due to the fact that as the altitude increases the velocity requirements for descent to and ascent from the earth's atmosphere increase; it is also partly due to the fact that the impulsive thrust plane change becomes less expensive. To a certain extent, this trade-off is discussed by Nyland (Ref. 2) who indicates that the combined aerodynamic-propulsive maneuvers are not likely to be advantageous above 1000 to 1500 n mi.

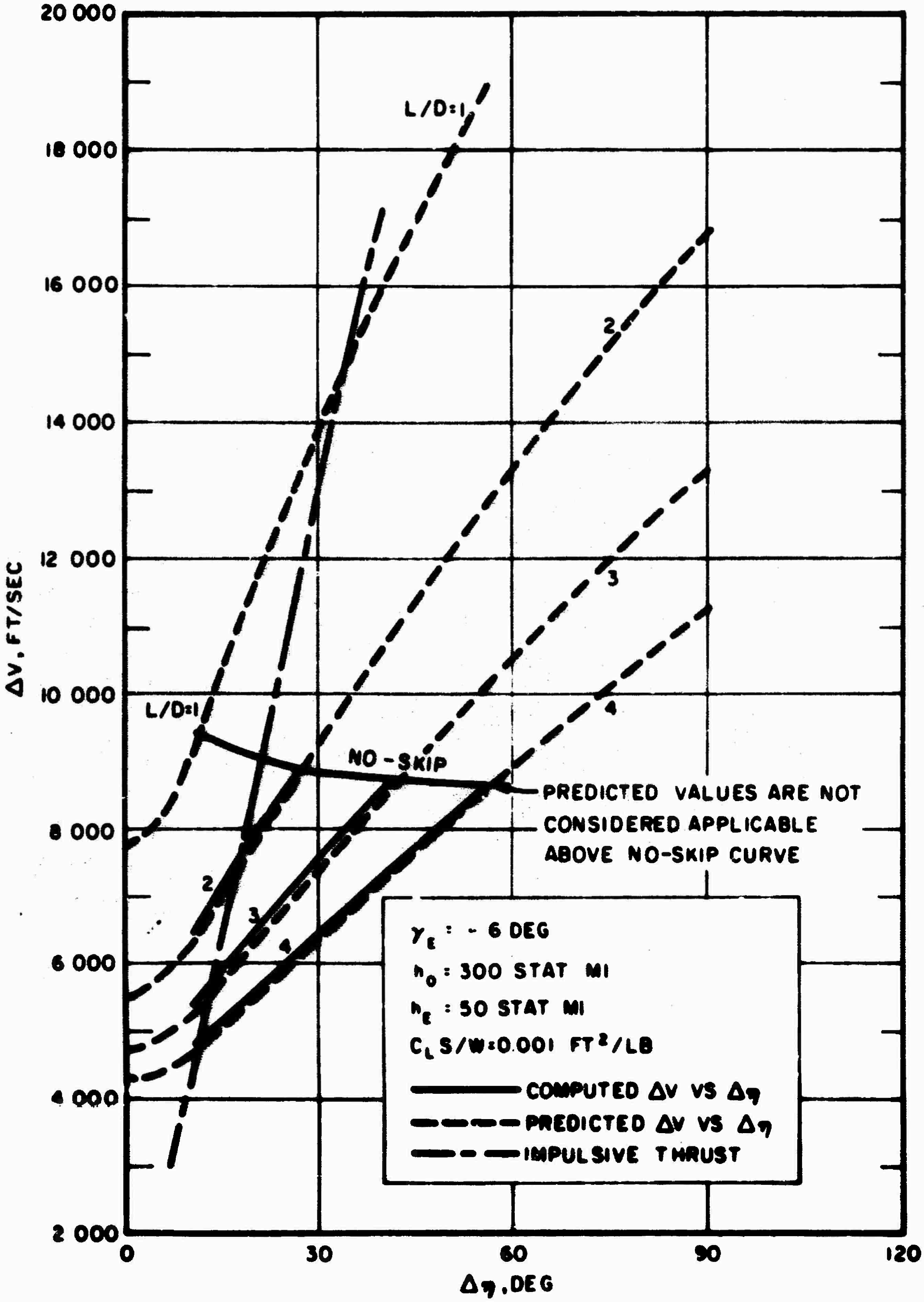


Figure 17. Comparison of Total Required Characteristic Velocities, $C_L S/W$ · 0.001 ft^2/lb

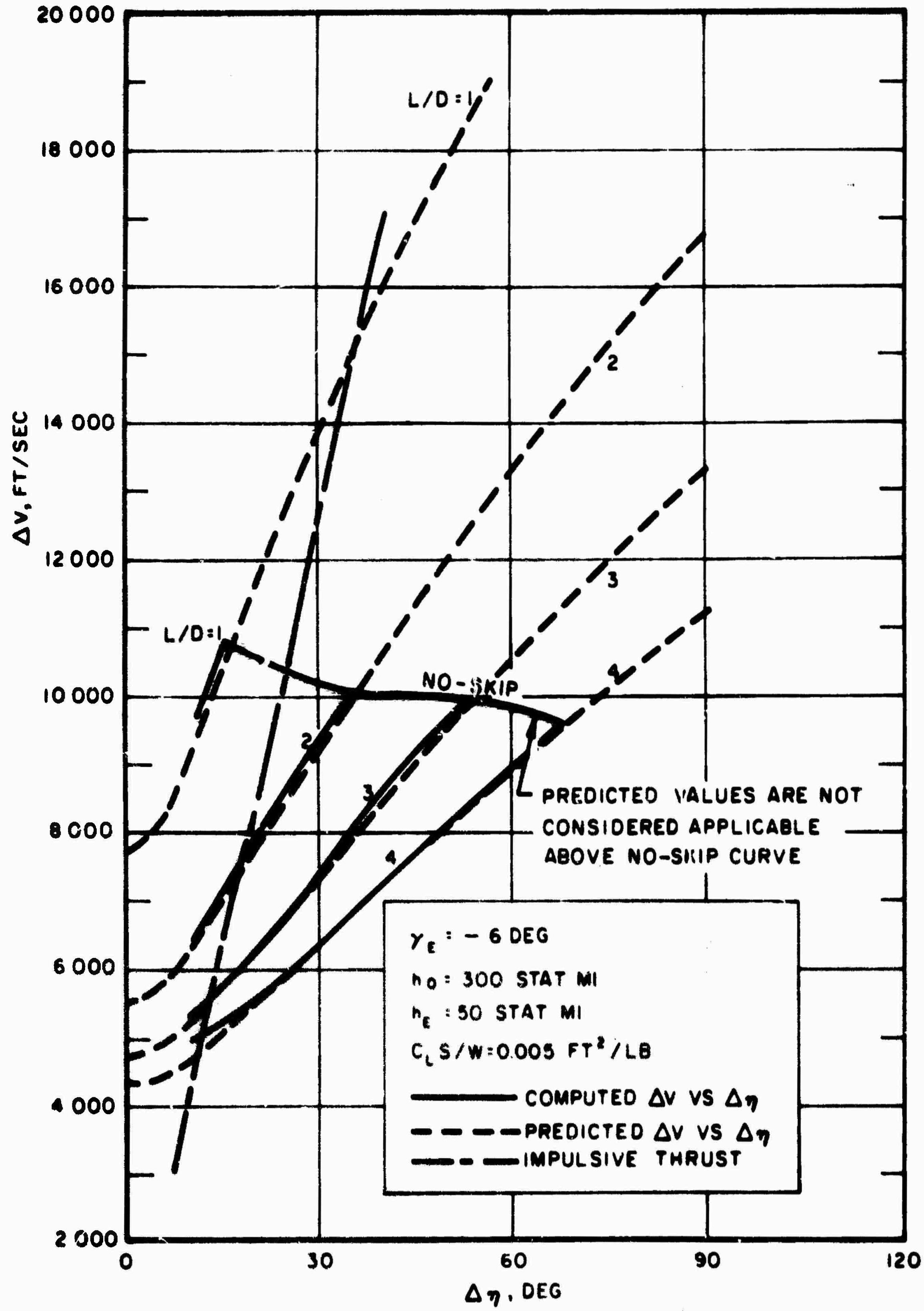


Figure 18. Comparison of Total Required Characteristic Velocities, $C_L S/W$ = 0.005 ft^2/lb

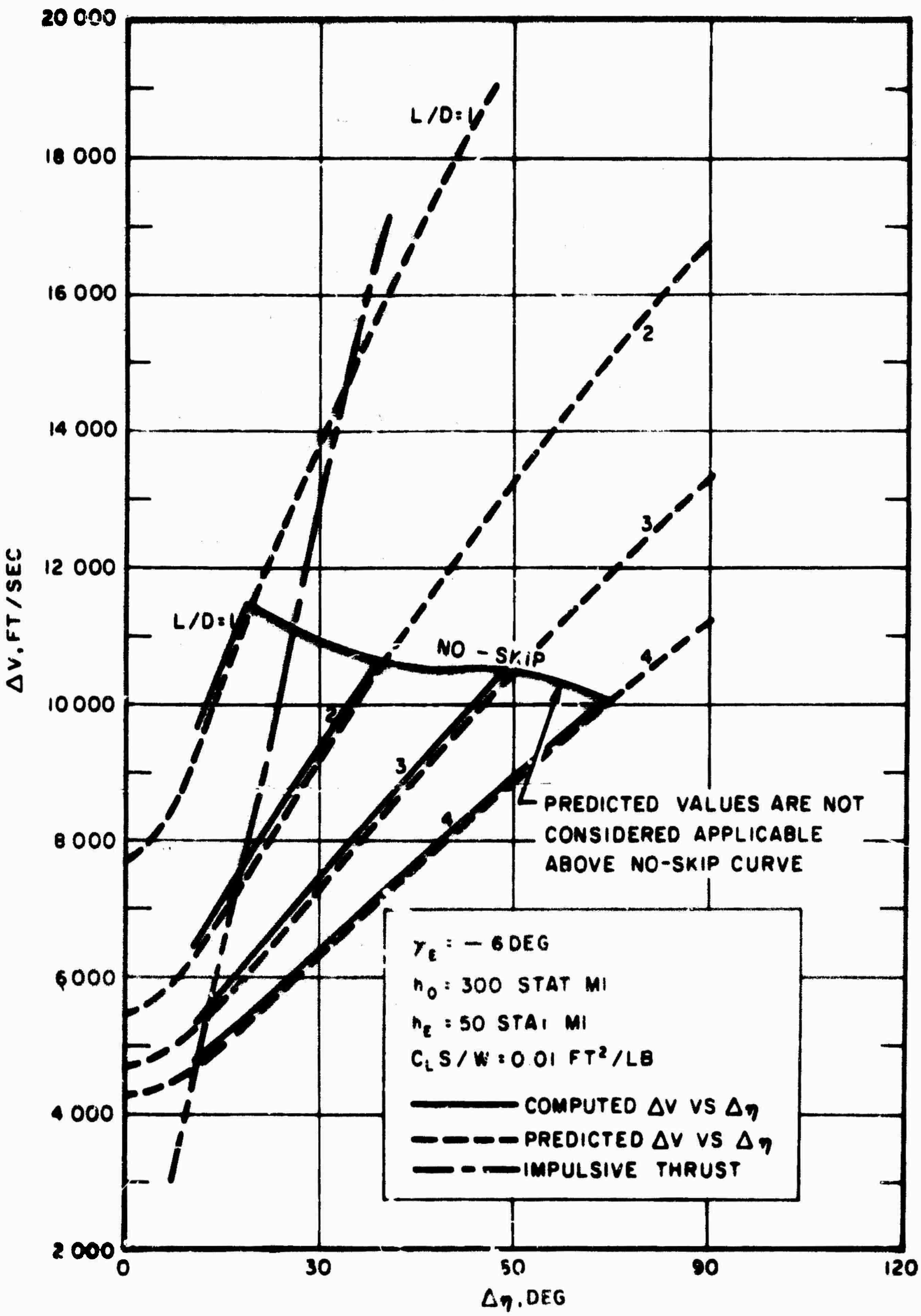


Figure 19. Comparison of Total Required Characteristic Velocities, $C_L S/W = 0.01$ ft^2/lb

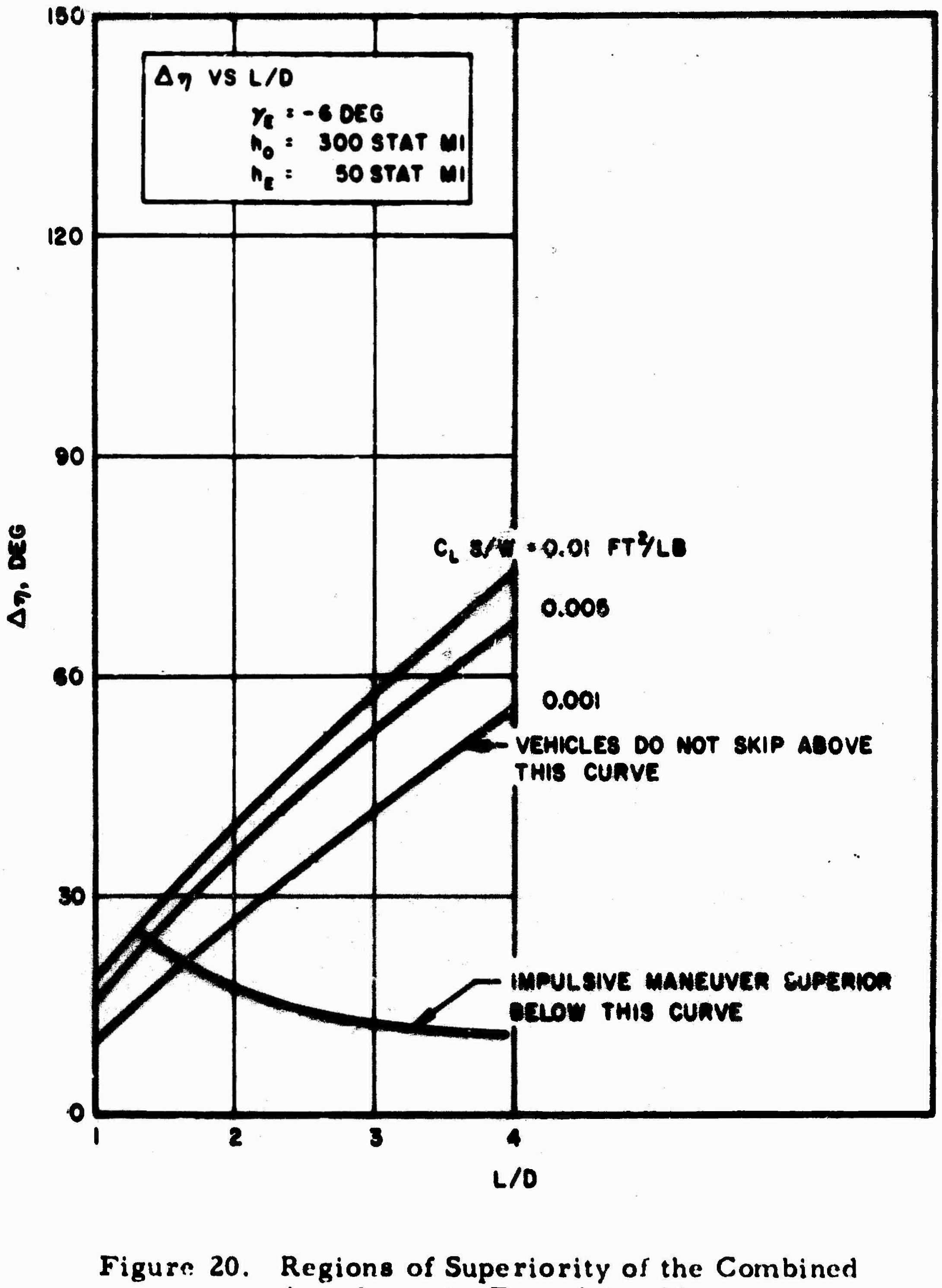


Figure 20. Regions of Superiority of the Combined Aerodynamic-Propulsive Maneuver

B. THE ANALYSIS OF NYLAND

In the approach taken by Nyland the vehicle first descends from its initial circular orbit (at 300 nautical miles altitude in this case) along either of two nominal paths until it reaches an altitude of 34.4 n mi. This altitude is assumed to be the limit of the sensible atmosphere throughout Nyland's analysis. The first of the descent paths considered is essentially a semi-ellipse; hence, the vehicle traverses a central range angle of 180 deg and has a zero flight path angle at the beginning of its re-entry at 34.4 n mi. The second descent path considered is chosen such that the vehicle will have traversed a central range angle of 90 deg by the time it reaches the re-entry altitude. The aerodynamic maneuver used to effect the plane change after re-entry is a hypersonic equilibrium glide minor-circle turn. This maneuver, which has been analyzed in detail (and in closed form) by Loh (Ref. 5), requires that the bank angle be continuously varied during the aerodynamic portion of the trajectory. In the class of minor-circle turns considered by Nyland, the aerodynamic forces on the vehicle are generally not sufficient to enable it to skip out of the atmosphere; therefore, at the end of the turning glide phase an increment of thrust is applied to the vehicle to initiate a transfer back to the initial orbital altitude. At that altitude, a final increment of thrust is applied to circularize the orbit.

The advantage of the aerodynamic plane change, following Nyland's technique (and London's, as well) depends for the most part upon the extent of the velocity losses associated with the portion of the trajectory in the earth's atmosphere. For the purposes of the study contained herein, a portion of the aerodynamic trajectory predicted by Nyland's method was simulated on a computer as a means of determining the effect of one of the simplifying assumptions made in his analysis. This simplifying assumption states that the drag losses incurred by the vehicle in the ascent phase of the trajectory can be neglected. Two examples were chosen; the first resulted in an aerodynamic plane change of 30 deg, and the second resulted in a 60 deg change. The minor-circle trajectory considered in both examples had a radius of

45 deg (i. e., the half angle of the cone, the base of which is the minor-circle and the vertex of which is at the center of the earth). An L/D ratio of 2 was used, together with the value of W/C_LS (equal to 136 lb/ft^2) consistent with the requirement for equilibrium glide and the initial conditions at re-entry. The re-entry conditions were uniquely determined by specifying the initial circular orbit altitude (300 n mi), the re-entry altitude (34.4 n mi), and the re-entry angle (0 deg). From the analysis of Loh (Ref. 5) it was therefore, determined that the following conditions would exist at the completion of the minor-circle turn:

$\Delta\eta$ deg	Altitude ft	Velocity ft/sec
30	204,000	19,800
60	166,800	10,000

These conditions were substituted into a computer program in order to determine the increment of velocity needed to transfer the vehicle back to the initial circular orbit altitude of 300 n mi. For this phase, the vehicle was trimmed down to a zero lift, minimum drag attitude such that L/D = 0. The ballistic coefficient, W/C_DA, was arbitrarily chosen to be 1000 lb/ft^2, which is considered representative of hypersonic vehicles in a minimum drag orientation. The computed values of ΔV together with those predicted by Nyland are tabulated below.

$\Delta\eta$ deg	ΔV predicted ft/sec	ΔV computed ft/sec
30	7,308	8,224
60	17,087	19,594

These differences are attributable to the drag encountered by the vehicle in the ascent phase, and it is felt that they can not be neglected. They diminish the superiority of the aerodynamic plane change predicted by Nyland over the impulsive plane change, as can be seen in Fig. 21. Therefore, the possible saving in ΔV of about 7800 ft/sec for a 60 deg plane change (mentioned in the introduction to the paper) is felt to be more on the order of about 5300 ft/sec.

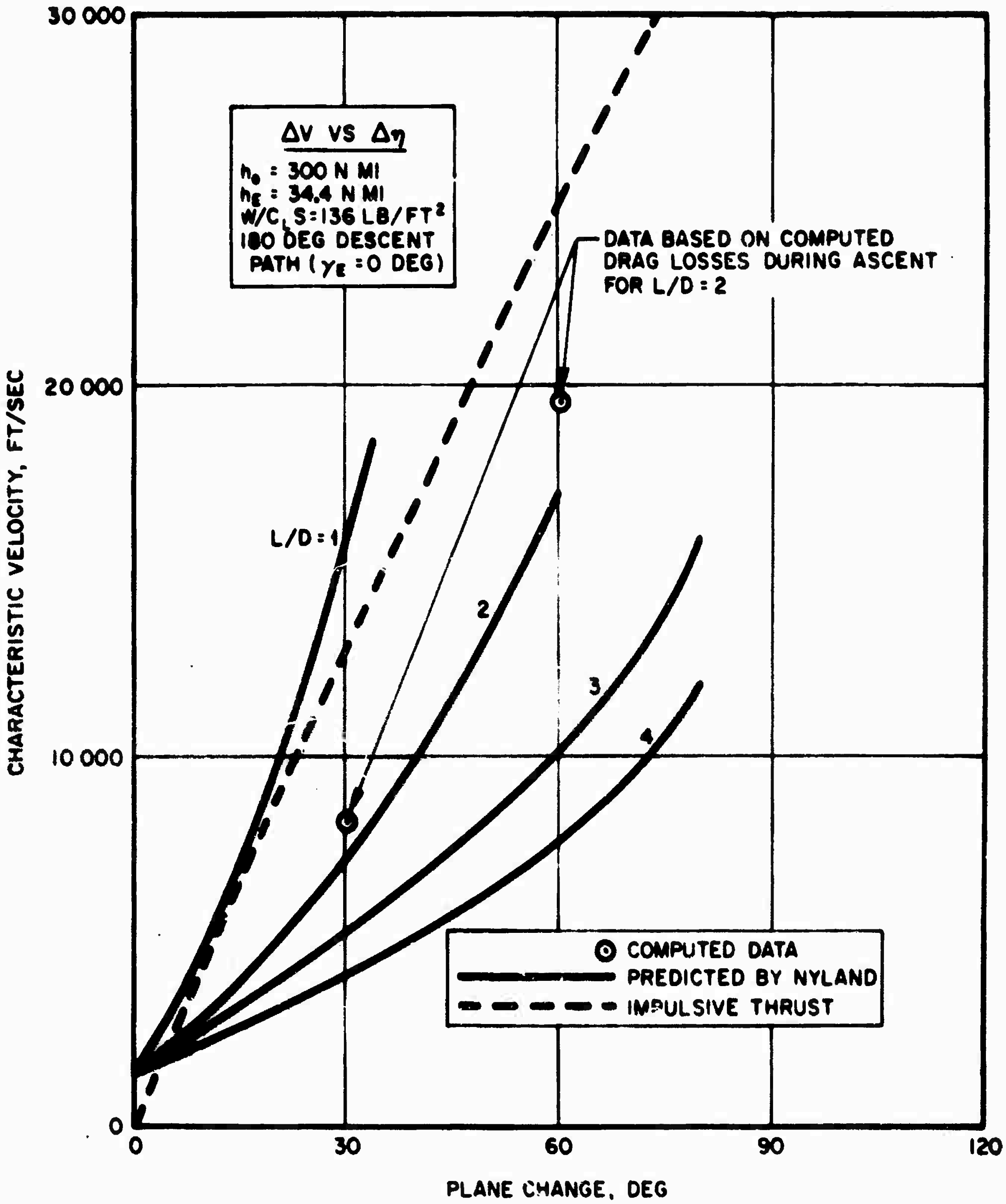


Figure 21. Comparison of Total Required Characteristics Velocities, Special Case

A prerequisite for equilibrium glide minor-circle trajectories is that the initial conditions (i.e., altitude, velocity, and flight path angle) be matched in a uniquely determined manner with the aerodynamic properties of the vehicle (i.e., L/D and W/C_LS). As mentioned previously, the required value of the parameter, W/C_LS, for the example trajectory considered by Nyland (h_o = 300 n mi, h_E = 34.4 n mi, γ_E = 0 deg), was 136 lb/ft^2. If it is desired to apply his analysis to vehicles with different values of W/C_LS, then suitable adjustments must be made in the initial conditions and/or radius of the minor-circle trajectory. For this reason, the results shown in Fig. 21 are not considered applicable to vehicles with values of W/C_LS different from that indicated.

Along the same lines, a certain amount of care must be taken in the interpretation of the results that correspond to the 90 deg descent path class of trajectories analyzed by Nyland. In such cases, the flight path angle is non-zero at re-entry; hence, a pull-up maneuver is required before the minor-circle turn can be initiated. This pull-up maneuver, based on the analysis of Loh (Ref. 6), is designed such that proper conditions for initiation of a specified minor-circle turn will result at its termination. The following example, presented in Nyland's paper, is included here in order to illustrate the procedure used to determine the pull-up maneuver consistent with a specified turning mission. It is assumed that an orbital plane change of 45 deg is desired and that the descent transfer path will be 90 deg. The lifting satellite vehicle has the following aerodynamic properties:

W/S = 30 lb/ft^2

C_L max = 0.6

C_L @ L/D max = 0.15

L/D max = 3

The conditions at re-entry (h_E = 34.4 n mi) are computed to be:

V_E = 25,876 ft/sec

γ_E = -4 deg

If it is assumed that the pull-up maneuver is to be flown at L/D max it is determined from Loh (Ref. 6) that the velocity at the end of pull-up will be 25,257 ft/sec and the altitude at end of pull-up will be 180,000 ft. However, the initial altitude required for the equilibrium glide minor-circle turn consistent with a velocity of 25,257 ft/sec is 198,000 ft. Therefore, Nyland proposes that an adjustment in the vehicle attitude be made for the pull-up phase in order to change the $W/C_L S$ by an amount that would result in the proper altitude of 198,000 ft at the end of pull-up. What is overlooked in the example presented by Nyland, however, is that any adjustment in $W/C_L S$ will also result in changing the L/D ratio of the vehicle which in turn will result in a different velocity at the end of the pull-up maneuver. This change is not accounted for in his results that correspond to the 90 deg descent path class of trajectories. Assessment of the resulting errors in ΔV and $\Delta \eta$, which are a consequence of this inconsistency, is difficult and, moreover, depends upon each mission and vehicle considered.

III. CONCLUSIONS

The results of this study indicate that the analyses of London and Nyland, while valuable from the standpoint of being amenable to closed form solution, have certain limitations that result, in part, from the simplifying assumptions made. It appears that London's analysis may be applied to the problem of the combined aerodynamic-propulsive plane change maneuver if the plane change angles are restricted to values below 30 to 40 deg. It is also evident, following London's technique, that the combined maneuver is not superior to the impulsive thrust plane change for vehicles with L/D ratios less than about 1.5, for the examples shown. And, if physical design limitations in the aerodynamic properties of vehicles are considered, it is not likely that savings in ΔV greater than about 4000 to 5000 ft/sec can be realized (such savings are still considered significant, however).

The results presented by Nyland, for the 180 deg descent path class of trajectories, are considered applicable to the extent that the drag losses associated with the ascent phase of the maneuver can be neglected. The results of this study indicate that these losses can not be neglected for large plane changes.

In any case, for certain situations, the combined aerodynamic-propulsive maneuver appears to be an attractive means available for reducing the characteristic velocity requirement of the orbital plane change.

REFERENCES

1. H. S. London, "Change of Satellite Orbit Plane by Aerodynamic Maneuvering," J. Aerospace Sci. 29, 3, 323-332 (March 1962).

2. F. S. Nyland, The Synergetic Plane Change for Orbiting Spacecraft, Memorandum No. RM-3231-PR. The RAND Corporation, Santa Monica, California (August 1962).

3. H. S. London, "Comments on Aerodynamic Plane Change," AIAA J. 1, 10, 2414 (October 1963).

4. G. M. Low, Nearly Circular Transfer Trajectories for Descending Satellites, NASA Technical Report R-3. National Aeronautics and Space Administration (1959).

5. W. H. T. Loh, "Dynamics and Thermodynamics of Re-entry," J. Aerospace Sci. 27, 10, 748-762 (October 1960).

6. W. H. T. Loh, "A Second-Order Theory of Entry Mechanics Into a Planetary Atmosphere," J. Aerospace Sci. 29, 10, 1210-1221 (October 1962).